Experimental investigation of mid-infrared laser action from Dy^{3+} doped fluorozirconate fiber

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Abstract— **Efficient continuous-wave laser operation at 2.982 µm is achieved with a Dy^{3}:fluoride fiber pumped using an inhouse-built 1.1 µm ytterbium (III) fiber laser. The laser output power reached is 554 mW, with a maximum slope efficiency of 18% with respect to the launched pump power. Additionally, the measured spontaneous luminescence within the visible wavelength range, under 1.1 µm pumping, is presented and attributed to excited state absorption (ESA). The influence of the ESA on the laser performance is discussed. The results confirm that high output powers from Dy: fluoride fiber laser pumped at 1.1 µm are possible.**

***Index Terms*—Mid infrared fiber laser, Dysprosium doped glass, Mid infrared sources**

I. Introduction

MID-INFRARED (MIR) fiber sources with emitting wavelengths covering the range stretching from 2.5 µm to 6 µm have many applications in remote sensing, medicine and defence [1,2]. Rare earth ion doped fiber lasers are an attractive alternative to other sources for the generation of MIR light. Fiber lasers are robust and cost-effective. They offer high output power with excellent beam quality and have good heat dissipation properties [1,2]. However, in order to access long operating wavelengths, low phonon energy host materials are needed. One promising low-phonon energy material is fluorozirconate glass (ZBLAN, composed of fluorides: ZrF_4, BaF_2, LaF_3, AlF_3, NaF). Significant progress in mid-infrared fluorozirconate fiber laser technology has been achieved in recent years. Most research within this area has been focused on the development of mid-infrared fiber lasers doped with erbium and holmium ions. Watt-level output power, broad tunability, Q-switched and mode-locked operation have been achieved [2-9].

However, much less attention has been paid to dysprosium ion-doped fluoride fiber lasers. Dysprosium ion-doped fluoride fiber lasers offer a possibility to extend the mid infrared emission towards longer wavelengths when compared with erbium and holmium ion doped fluoride lasers.

First, CW (Continuous Wave) laser operation from Dy^{3+}: ZBLAN fiber was reported by Jackson [10]. In that contribution, the fiber laser was emitting 275 mW maximum output power, with a slope efficiency of 4.5%, under 1.094 µm pumping. The second successful demonstration of a Dy^{3+}: ZBLAN fiber laser, pumped at 1.088 µm, was presented in [11]. In this work, a laser slope efficiency of 23% was achieved. However the output power was limited to 100 mW. The highest slope efficiency for CW operation of dysprosium ion doped fluoride fiber lasers has so far reached 51% under resonant pumping by an erbium ion doped fluoride fiber laser operating at 2.8 µm (80 mW maximum output power) [12]. Moreover, a wavelength tunable Dy^{3+}-doped ZBLAN fiber laser was also recently presented by Majewski *et al.* [13]. Tunability over 600 nm in the spectral region between 2.8-3.4 µm was achieved. A CW dysprosium fluoride fiber laser pumped at 1.7 µm with a Raman laser was shown in [13]. This laser had a slope efficiency 21% and generated about 200 mW of output power. In 2006 Tsang *et al.* presented a Dy^{3+}-doped ZBLAN fiber laser pumped by a ~1.3 µm Nd:YAG laser. The slope efficiency for this laser was 20% and the maximum output power was below 200 mW [14]. In summary, so far, MIR laser action in Dy^{3+}: ZBLAN fiber pumped at 1.1 µm, 1.3 µm, 1.7 µm and 2.8 µm has been successfully demonstrated. However, the maximum output powers reported so far from such Dy^{3+}: ZBLAN fiber lasers did not exceed 300 mW. One of the reasons for this situation is that high power pump lasers operating at 1.3 µm, 1.7 µm and 2.8 µm still have limited commercial availability. Therefore, from the practical point of view, the application of cost-effective pumping at 1.1 µm with ytterbium ion doped fiber lasers seems to be the most reasonable option. Ytterbium ion doped fiber lasers with high brightness are readily commercially available.

In this contribution, the lasing properties of the Dy^{3+}:

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ZBLAN fiber laser are studied. The results show that more than 554 mW of output power at 3 µm and with a slope efficiency of 18% can be achieved by a Dy^{3+}: ZBLAN fiber laser pumped at 1.1 µm. It is believed that this is so far the highest output power generated in a dysprosium fluoride fiber laser pumped at 1.1 µm.

The paper is divided into four sections. After the introduction, section 2 describes the experimental set-up, which was used to obtain MIR laser action from the Dy^{3+}: ZBLAN fiber. In section 3 the results obtained are presented and discussed. Finally, conclusions are drawn in section 4.

II. EXPERIMENTAL SET-UP

Fig.1 presents a simplified energy level diagram of Dy^{3+} in fluoride glass. The mid-infrared laser action took place between the $^6H_{13/2}$ upper lever and the ground state $^6H_{15/2}$. The lifetime of the upper laser level $^6H_{13/2}$ was 0.63 ms [15]. The absorption cross section at 1.1 µm was equal to 3×10^{-25} m^2 [10]. The pumping at 1.1 µm populates the thermal coupled levels: $^6H_{7/2}$ and $^6F_{9/2}$. The $^6H_{7/2}$, $^6F_{9/2}$, levels and $^6H_{9/2}$, $^6F_{11/2}$, and $^6H_{11/2}$ levels are depopulated non-radiatively due to multi-phonon quenching [16].

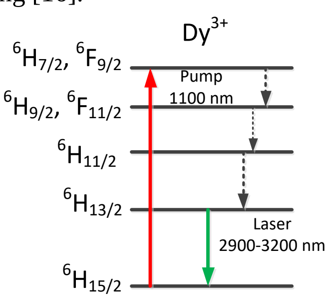

Fig. 1. Simplified, energy-level diagram of Dy^{3+} in fluoride glass, showing the pump and laser processes.

A schematic diagram of the experimental set-up is presented in Fig. 2. A home built single mode ytterbium fiber laser emitting at 1.1 µm with an output power around 8 W serves as a pump. The ytterbium laser uses a Fiber Bragg Grating (FBG) to fix the operating wavelength at 1.1 µm. A pump wavelength of 1.1 µm was chosen because it matches the maximum absorption for the $^6H_{15/2}\rightarrow(^6H_{7/2}$, $^6F_{9/2})$ transition. The pump laser output beam was collimated and focused onto the core of the Dy^{3+}: ZBLAN fiber. The incident pump power was estimated by coupling the pump to the fiber core at one end of a silica fiber with a similar core diameter and numerical aperture (NA) as the Dy^{3+}: ZBLAN fiber used in the laser, and measuring the power transmitted through the silica fiber at the other end. The launching efficiency obtained was around 50-55%.

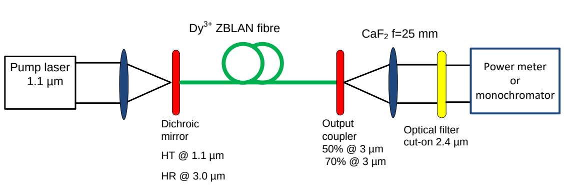

Fig. 2. Schematic diagram of the mid-infrared fiber laser.

700 mm of Dy^{3+} doped ZBLAN fiber was used as the gain medium. The selected fiber length should provide around 98% absorption of the pump power. The fiber had a 1000 ppm core doping concentration of Dy^{3+} (Le Verre Fluoré), a core diameter of 15 µm and single mode operation for wavelengths above 2.5 µm. The fiber was perpendicularly cleaved using a fiber cleaver with regulated tension. The proper tension was obtained by trial and error. The laser cavity was formed by butt coupling one end of the fiber with a dichroic mirror (highly reflective for the wavelengths stretching between 2.8—3.2 µm and highly transparent for wavelengths around 1.1 µm), while the other end was butt-coupled with a 50% or 70% reflector (for the signal wavelength only), which acted also as an output coupler. Additionally, output coupling relying on the Fresnel reflection from the fiber end was also investigated.

The output from the fiber laser was collimated using a CaF_2 lens with f=25 mm (110-5105E Eksma Optics). The pump wavelength was rejected by an optical filter with a cut-on wavelength of 2.4 µm (Edmund Optics #68-659). The output power was measured using a thermal power sensor (S401C Thorlabs). The input fiber end was placed in a stainless steel V-groove, covered with thermal conductive paste in order to improve the heat dissipation.

The emission generated by the gain fiber in the spectral range between 2.5 µm-3.5 µm was monitored using a 150 mm optical monochromator (MSH-150 LOT-Quantum Design GmbH) with a diffraction grating blazed at 4 µm coupled to a thermo-electrically cooled MCT detector (Vigo System PV-4TE-6). In order to improve the signal-to-noise ratio a lock-in detection technique was employed.

III. RESULTS

Fig. 3 shows the spectral dependence of the mid-infrared fiber laser emission together with the measured Amplified Spontaneous Emission (ASE) spectrum. As expected, the laser emission was very narrow compared with the ASE spectrum. This, unambiguously verifies the occurrence of the laser action. The broadband ASE spectrum suggests that the laser wavelength can be tuned over a 2.8-3.4 µm wavelength range.

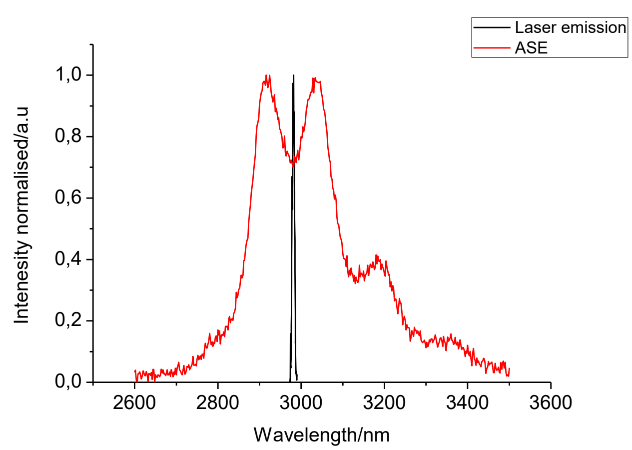

Fig. 3. Laser emission in comparison with the Amplified Spontaneous Emission (ASE) spectrum recoded from Dy^{3+}:ZBLAN fiber.

Figure 4 shows the dependence of the measured laser output power on the launched pump power for a 700 mm long fiber with 98.5%-50% and 98.5%-70% end face reflectivities for the signal wave. 18% slope efficiency and 554 mW maxiumum output power was obtained for a 98.5%-50% cavity. For the cavity with 98.5%-70% end face reflectivities a slope efficiency of 13.5% and a maximum output power of 467 mW were recorded. A similar laser threshold of around 300 mW was measured for both cavities. The high threshold can be attributed to the quasi- three level laser structure of the $^6H_{13/2} \rightarrow {}^6H_{15/2}$ transition.

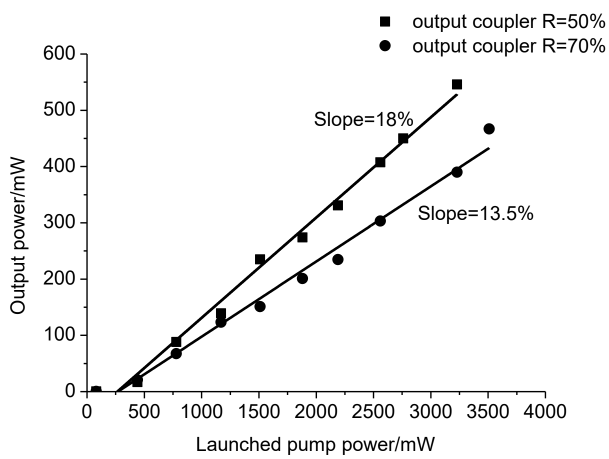

Fig. 4. Output power of 3 µm Dy^{3+}:ZBLAN fiber laser as a function of lunched pump power for 98.5%-50% and 98.5-70% cavities.

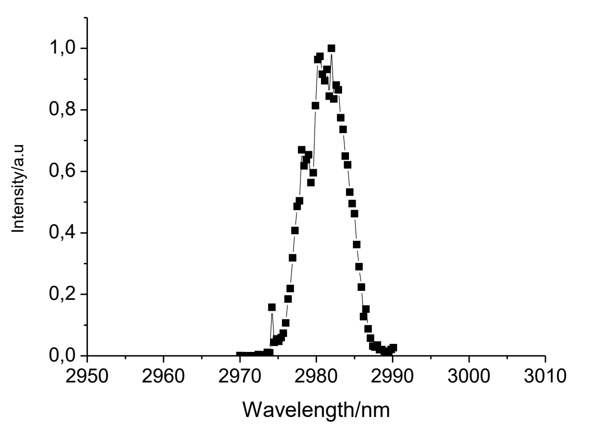

Fig. 5. Measured Dy^{3+}:ZBLAN fiber laser output spectrum for 98.5-70% cavities for lunched pump power of 1060 mW.

Fig. 5 presents the emission spectrum generated by the laser based on a 98.5-70% cavity for a launched pump power of 1060 mW. These results show that the laser operated at 2.982 µm with a full width half maximum (FWHM) bandwith of 6 nm.

Figure 6 shows the measured laser output power as a function of the lunched pump power for a 700 mm long fiber with a 98.5%-4% (Fresnel reflection from the fiber end) cavity. A 3% slope efficiency and a maximum output power of 34 mW were obtained. For this cavity set-up pump power threshold was 2500 mW. As expected, a higher pump power is needed to obtain laser action because there is a lower amount of feedback in this cavity. These results show that in this case the fibre gain was not sufficient to obtain efficient operation but this design is relatively simple because it only required one dichroic mirror at the fiber input. Power levels generated in this cavity scheme were nevertheless sufficient for sensing applications.

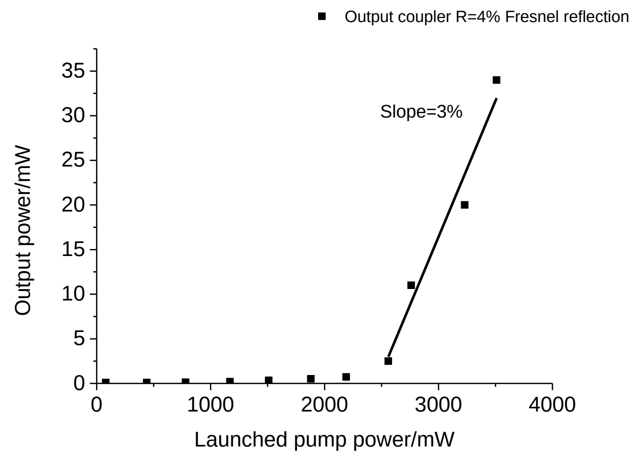

Fig. 6. Output power of 3 µm Dy^{3+}:ZBLAN fiber laser as a function of lunched pump power for 98.5%-4% cavity.

Under strong pumping at 1.1 µm white luminescence was observed from the fiber. This result suggests that up-conversion was occurring. Due to the fact that the doping concentration of the fiber was low, around 1000 ppm, this up-conversion mechanism can most likely be attributed to excited state absorption (ESA). Therefore, in order to better understand this phenomenon, the white luminescence was collected from the side of the Dy^{3+}:ZBLAN fiber, using a large core (1000 µm diameter, NA=0.5) polymer fiber, and subsequently analyzed by means of a spectrometer (Ocean Optics S2000-UV-VIS). The recorded spectrum of visible and near infrared emission pumped at 1.1 µm is shown in Fig. 7. Four emission bands centered at 476 nm ($^4F_{9/2} \rightarrow {}^6H_{15/2}$), 571 nm ($^4F_{9/2} \rightarrow {}^6H_{13/2}$), 657 nm ($^4F_{9/2} \rightarrow {}^6H_{11/2}$) and 810 nm ($^4F_{9/2} \rightarrow {}^6H_{9/2}, {}^6F_{11/2}$)+($^4F_{9/2} \rightarrow {}^6H_{7/2}, {}^6F_{9/2}$), were recorded. The measured emission was in good agreement with the results obtained from the $^4F_{9/2}$ transition in Dy^{3+}: ZBLAN glass by other authors [17, 18]. Therefore it can be concluded that the ESA mechanism populates the $^4F_{9/2}$ transition. The $^4F_{9/2}$ is a long-lived level with a measured lifetime of approximately 1 ms [17]. Hence, a significant population can build up at this energy level.

The ESA mechanism can be explained as follows: first ESA1 occurs from the highly populated upper laser level $^6H_{13/2}$ to the $^6F_{5/2}$ level. Note that the energy difference between the $^6H_{13/2}$ and $^6F_{5/2}$ levels (8858 cm^{-1}) is nearly resonant with the pump photon energy at 1.1 µm. ESA2 occurs between the level $^6F_{5/2}$ (populated by ESA1) and the long-lived $^4F_{9/2}$ level (the energy difference between the $^6F_{5/2}$ and $^4F_{9/2}$ levels is 8748 cm^{-1}). The ESA transitions are depicted in Fig. 8. ESA from the upper laser level $^6H_{13/2}$ is undesired because it reduces the population inversion for the $^6H_{13/2} \rightarrow {}^6H_{15/2}$ transition. It also increases the laser threshold and wastes pump energy. ESA could be a major reason for why the slope efficiency of the laser was only 18% while from the Stokes limit one would expect it to be around 37%. Another possible explanation of up-conversion process might be a resonantly enhanced 2-photon ESA. For instance, resonance between the 1.1 µm pump laser and the energy difference between the $^6F_{5/2}$ and $^4F_{9/2}$ states. The $^6F_{5/2}$ level could be depopulated through this process as well. This type of process would not depend on the lifetime of the $^6F_{5/2}$ level.

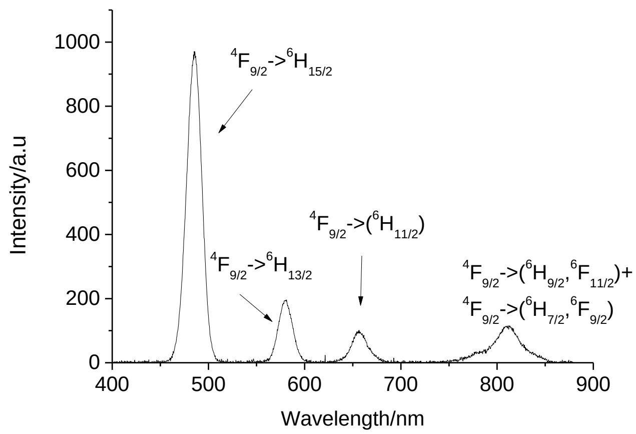

Fig. 7. Up-converted Dy^{3+}: ZBLAN emission spectrum originated from $^4F_{9/2}$ pumped at 1.1 µm.

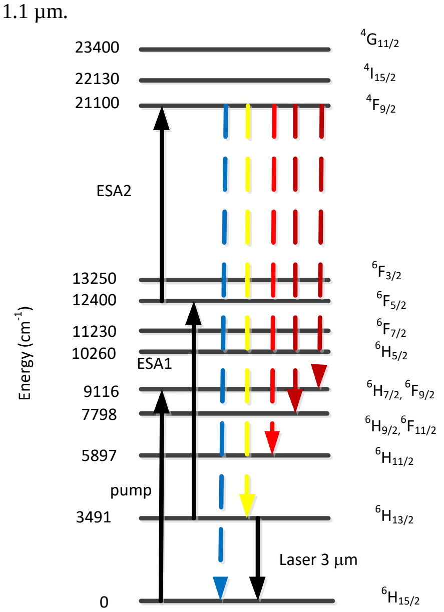

Fig. 8. Detailed Dy^{3+}: ZBLAN energy level scheme with ESA upconversion excitation scheme and visible transitions.

IV. CONCLUSION

In this letter we reported, to the best of our knowledge, the highest output power emitted at around 3 µm from a Dy^{3+}: ZBLAN fiber laser which was pumped at 1.1 µm. A maximum slope efficiency of 18% and an output power of 554 mW were obtained for a 98.5%-50% end face reflectivity laser cavity. Additionally, ESA mechanisms that degrade the laser performance were experimentally investigated and discussed. These results show that obtaining high output powers from Dy:ZBLAN fiber laser pumped at 1.1 µm is possible. In the near future concepts for power scaling will be implemented.

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